AD P000219

CHARACTERISTICS OF FLIGHT SIMULATOR VISUAL SYSTEMS

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ABSTRACT

Some of the findings of AGARD FMP WG10 are discussed. Image detail and resolution are two characteristics of visual simulation systems which seem to be significant in determining pilot performance in a simulator. MTFA has been found to be a reliable metric for predicting target acquisition performance, however, present measurement techniques are not suitable for moving imagery. Reliable techniques for the measurement of both image detail and resolution need to be developed. Apparent motion as opposed to real motion is also discussed. Neither the effect of visual simulation characteristics on apparent motion nor the effect of apparent motion on pilot performance are well understood and require further research.

INTRODUCTION

Working group 10 was established by the Flight Mechanic's Panel (FMP) of the Advisory Group for Aerospace Research and Development (AGARD) in March 1979 to consider and report the characteristics of flight simulator visual systems. (1) The main task of this working group was to identify and define the physical parameters which characterise and determine the fidelity of visual systems, and to recommend techniques for measuring these parameters. This paper is based on the findings of the working group.

Considerable progress has been made in visual simulation technology, particularly in the area of computer image generation. It is still necessary, however, to make many compromises during the design of a visual system before finding a solution which is both technically sound and economically feasible. Ideally, the tradeoff decisions which must be made require answers to the following questions:

(a) What visual cues does a pilot use when flying aircraft in specific missions or tasks?

(b) How should the characteristics of the visual simulation system be specified to enable those cues to be presented to the pilot with sufficient fidelity to allow the given task to be performed?

(c) How well should a pilot be able to perform to obtain useful training, or to provide useful data to the research engineer or psychologist, or to enable his performance in an aircraft to be predicted?

Some of these questions have been addressed by the AGARD joint working group of the Aerospace Medical and Flight Mechanic's Panels on fidelity requirements of simulation for training purposes. (2)

It is apparent, however, that complete answers to these questions do not exist and that the designer must rely on a combination of data currently available, experience with previous simulations and intuition.

The FMP working group 10 was neither tasked with nor qualified for the address of the three questions, but restricted itself mainly to the question of which parameters should be measured and how they should be measured. If we are to be able to relate pilot performance to a set of physical parameters, we must have a relevant set of parameters and reliable methods of measurement.

The working group divided the physical parameters into three basic categories of spatial, energy and temporal properties corresponding to the fundamental quantities of length, mass and time. The following is a discussion of certain aspects of each category.

SPATIAL PROPERTIES

This section of the report covers metrics associated with field of view, depth, geometric distortions and scene content. The last of which is sufficiently intriguing to be discussed at length. The term scene content is used here to describe scene complexity or image detail density and is not related to the artistic nature of the scene. It is recognised that artistry can have a considerable impact on the usefulness of a scene but no attempt was made to define this parameter in the report.

The current nature of computer-generated systems does not allow highly detailed images. Users are constantly demanding more detail. There is evidence to suggest that an observer's ability to judge his position and velocity relative to his immediate environment depends not only upon the quality and geometry of the visual stimuli but also upon their quantity. Answers to the second question raised in the introduction therefore may require measurement of image content. These measures may assist users to specify their requirements.

Cohen et al[3] measured the spectrum of the luminance in natural scenes by analysing television video signals. They found that the luminance spectra of natural scenes could be approximated by a function that varied with the inverse square of the spatial frequency. They also found that the power spectrum of randomly spaced luminance steps having a random distribution of

luminance values also exhibits the inverse frequency squared function. They speculated, therefore, that natural scenes can be thought of as an array of step luminance transitions having random spatial and magnitude distributions.

This led one member of the working group to speculate that scene content could be described by the density of the luminance or colour transitions within the scene.

The number of luminance or colour transitions in a given solid angle of a visual scene may be measured by an edge scanner that counts the number of observable edges in a given scan direction. Take several samples across the scene in orthogonal directions and obtain an average number of edge transitions in each direction. The square root of the product of these two numbers is a measure of scene complexity. The luminance/colour transition density is then obtained by dividing this number by the solid angle subtended by the scene. A number of photographs were analysed and values varying from 0.11/deg.^{2} for a colour photograph of a wooded canyon to 0.003/deg.^{2} for a CGI country scene were obtained.

A certain amount of research would be necessary to establish the value of such a metric and whether other measures might be more appropriate.

ENERGY PROPERTIES

Those properties associated with radiant power were deemed to belong in this section of the report. Luminance, contrast, colour and noise were fairly easy to define and established techniques exist for their measurement. Colour is somewhat interesting because little data exists to indicate its usefulness in a simulator either for training or research. Resolution, which should perhaps belong in the spatial section, is the most difficult to specify and is probably the most familiar characteristic of a visual system.

Our understanding of resolution is only slightly greater than that of scene content. The report defined the resolution of a visual system as its ability to present small recognisable details. In recognition of the fact that flight simulators invariably require moving imagery, the definition should probably be modified to include the ability to present small movements or changes in shape of image details. The ability of the human visual system to discriminate fine detail is termed visual acuity. The various types of visual acuity are defined as follows:

(a) Minimum separable acuity is the ability of the eye to separate two small objects.

(b) Minimum perceptible acuity is the eye's ability to detect a small object.

(c) Vernier acuity is the ability to align two objects such as two straight lines.

(d) Stereoscopic acuity is the ability to detect a difference in depth between two objects using both eyes.

(e) Motion acuity is the ability of the eye to detect the motion of small objects.

The significant aspects of each type of acuity are described in the report. They are all relevant to visual simulation system design although usually only the first of the five, minimum separable acuity, is specified in a procurement. Minimum spearable acuity (often called visual acuity, or V.A.) has an important effect on all types of acuity but the relationship is seldom linear and other parameters may have even greater significance. Matsubayashi (4) found that reducing the acuity of one eye to 0.3 had little effect on stereoscopic acuity whereas further reduction had considerable effect. Researchers at the Boeing Aerospace Company have recently obtained similar results when the acuity of both eyes was reduced.

Minimum perceptible acuity is a function of the length of the object. A human hair is clearly visible on a CRT driven from a television camera even though its width is an order of magnitude less than the size of object which the system bandwidth might be expected to display. It is interesting to note that algorithms emulating such performance are being developed by CGI systems and the results are proving very effective.

Vernier acuity is an important factor in flight tasks such as hovering, formation flying and inflight refueling. Continuous sampling processes such as the horizontal scan of a normal television camera allow vernier acuity to approach that of the human visual system even though the minimum separable acuity may be quite low. Discrete sampling processes such as a raster structure severely limit vernier acuity although it is interesting to note that relatively high vernier acuity can be obtained across the raster of a CRT providing the raster structure is visually suppressed. Temporal characteristics such as threshold and hysteresis will also affect both vernier acuity and motion acuity.

All the above-mentioned types of acuity are greatest, i.e., have lower angular thresholds in the foveal region of the eye. Figures 1 and 2 show how V.A. and motion acuity vary with retinal eccentricity. The effect of luminance and contrast on visual acuity are discussed at length in the working group report but the general effect on V.A. is shown in Figures 3 and 4.

Measurement of Resolution (Minimum Separable).

The concept of limiting resolution has been used by the television industry for many years. It is, however, an unreliable measure. Differences of up to 25% can be obtained by merely changing the length and number of lines in the displayed bar patterns and even casual observers can detect considerable differences in

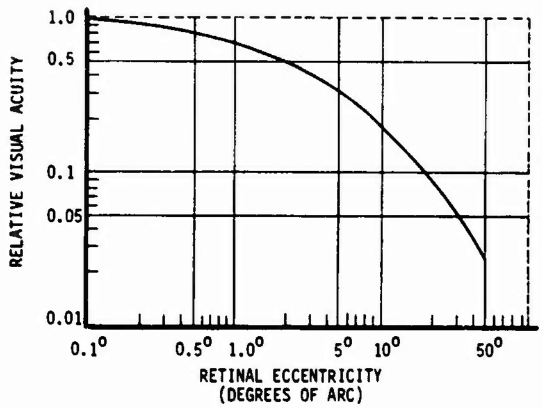

FIGURE 1 VARIATION IN VISUAL ACUITY WITH RETINAL ECCENTRICITY (FROM W.S. SMITH)

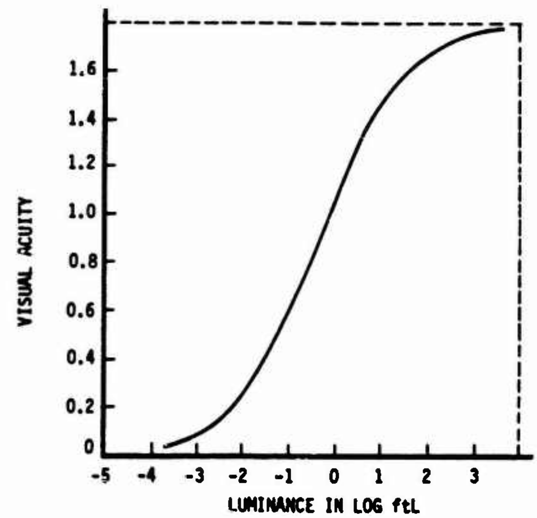

FIGURE 3 VARIATION OF V.A. WITH LUMINANCE (CONE VISION ONLY). (FROM KONIG)

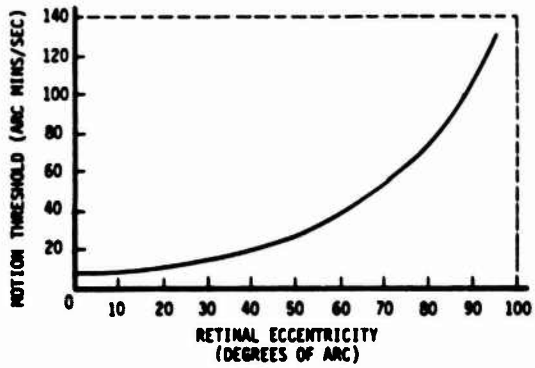

FIGURE 2 MOTION THRESHOLD FOR CIRCULAR TARGET SUBTENDING 0.5 DEGREE. BACKGROUND LUMINANCE - 14 ftL; TARGET LUMINANCE - 7 ftL. (FROM SALVATORE 1978)

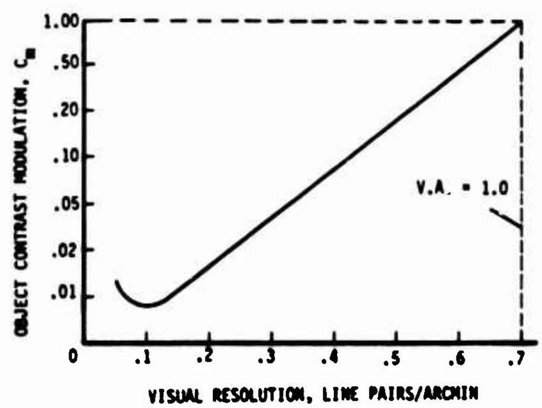

FIGURE 4 OBJECT CONTRAST MODULATION, $\Delta B/2B_{av}$, NECESSARY FOR EYE TO RESOLVE A PATTERN OF ALTERNATING DARK AND BRIGHT BARS OF EQUAL WIDTH (B_{av} = 35 cd/m^2)

picture quality between systems having the same limiting resolution. The most widely accepted method for measuring resolution is the generation of a Modulation Transfer Function (MTF) using a sinusoidally modulated test pattern. The input test pattern is 100% modulated and the output modulation is plotted against spatial frequency which produces a plot similar to that shown in Figure 5. Such a curve gives a fairly adequate description of the resolution characteristics of most displays and can be used to predict operator performance for a number of visual tasks.

Care should be taken when specifying or interpreting MTF's. Optical systems generally have a different MTF for radial and tangential lines and any sampling techniques such as a raster structure or the shadow mask of a colour CRT will have a considerable effect on spatial frequencies greater than half the sampling frequency.

Although the MTF curve is a useful measurement for a visual system, it does not give a unique figure of merit enabling comparisons to be made between visual systems. Charman and Olin[5] proposed the use of the area between the MTF curve and the threshold detectability curve as a measure of image quality for photographic systems. The metric was called the threshold quality factor and has been applied to electrooptical systems in general under the name of modulation transfer function area (MTFA). The threshold detectability curve would normally be that of a human observer but may be modified by other system characteristics. Figure 6 shows typical MTF curves for an optical display system together with a threshold detectability curve for a typical observer. The areas between the threshold detectability curve and the MTF curves represent the radial and tangential MTFA for this particular system under the conditions of the measurement. Snyder ([6]) has shown that MTFA can be used to predict probability of recognition of real-world targets displayed on a CRT. Varying amounts of video noise were added to elevate the detectability threshold curve.

An interesting experiment was performed by Boynton and Boss ([7]) to determine the effect of contrast and illumination on target recognition. They presented arrays of small dark circles to a number of observers. Half the arrays had a square substituted for one of the circles and the task was to say whether a square was present or not. The illumination of the arrays and the contrast of the targets were varied and the percentage of targets reported was plotted against time (see Figures 7 and 8).

The design of the apparatus was such that high contrast could be maintained at spatial frequencies somewhat beyond those useable by the eye and the control of contrast was uniformly applied to all spatial frequencies.

The system resolution and observer threshold curves relevant to the case of 100% contrast targets and variable luminance can be depicted as in Figure 9. The resulting MTFA values can then be plotted against target recognition performance as in Figure 10.

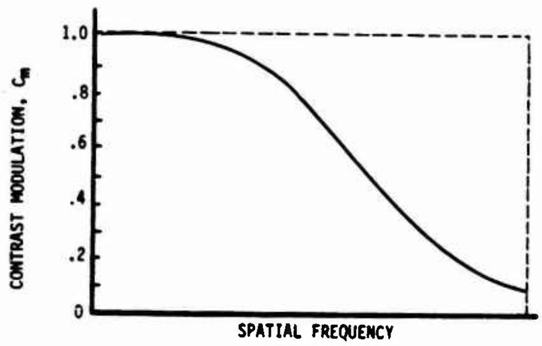

FIGURE 5 TYPICAL MTF CURVE

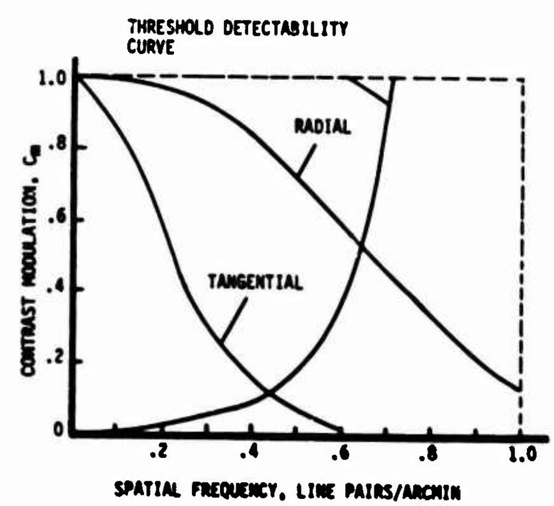

FIGURE 6 CONTRAST MODULATION CURVE FOR A WIDE-FIELD PUPIL-FORMING DISPLAY.

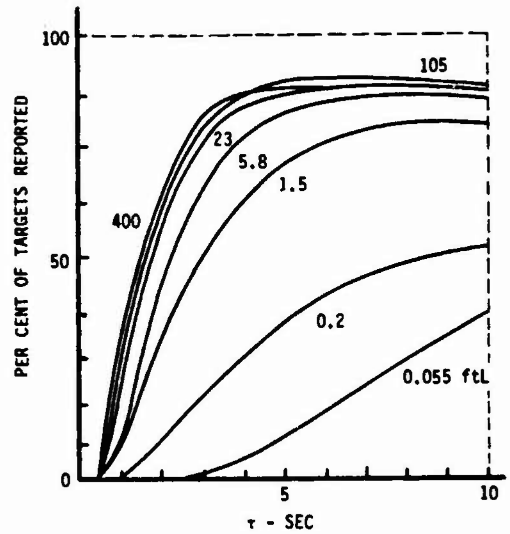

FIGURE 7 AVERAGE TARGET ACQUISITION CURVES FOR 100% CONTRAST TARGETS AT DIFFERENT BACKGROUND LUMINANCE LEVELS. (FROM BOYNTON & BOSS)

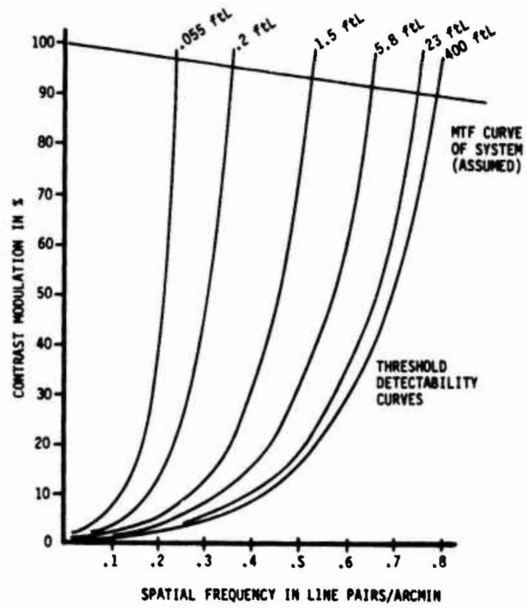

FIGURE 9 MTF OF APPARATUS AT 100% CONTRAST. THRESHOLD DETECTABILITY CURVES INTERPOLATED FROM FIGURES 3 & 4

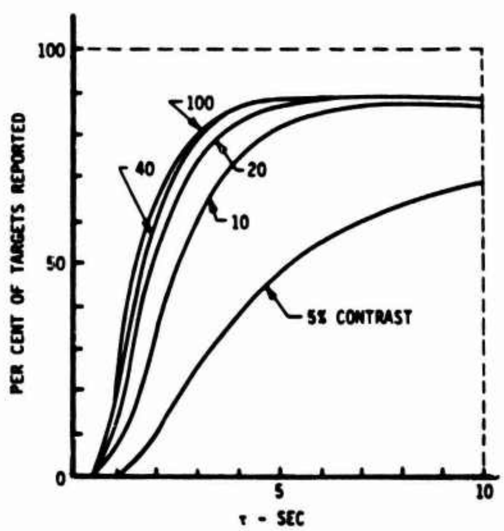

FIGURE 8 AVERAGE TARGET ACQUISITION CURVES FOR 400 ftL AT DIFFERENT CONTRAST LEVELS. (FROM BOYNTON & BOSS)

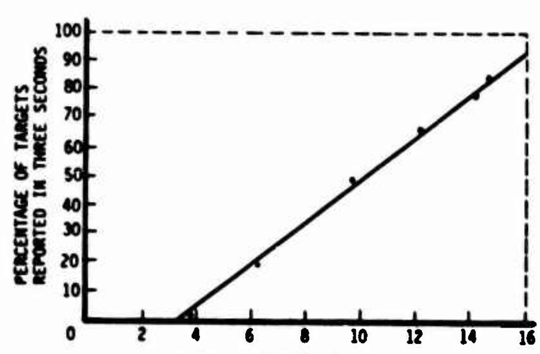

FIGURE 10 RELATION BETWEEN MTFA AND TARGET RECOGNITION USING LUMINANCE AS A VARIABLE.

The percentage of targets reported in three seconds has been used as a measure of observer performance. A three-second search task not only seems relevant to many flight tasks but was also used by Boynton in his own analysis of the data. Figure 10 shows a surprising degree of correlation between MTFA and observer performance under varying illumination levels.

In general, it would appear that MTFA can be used to predict observer performance in target acquisition tasks providing that the system MTF exhibits normal behaviour.

Dynamic Aspects of Resolution.

MTF curves and threshold detectability curves are normally obtained using static images. Unfortunately, the image presented to a pilot on a visual simulation system is seldom static. A much more relevant metric would be one that measures dynamic resolution. System MTF can be degraded considerably by such factors as TV camera lag, display decay time and various aliasing effects.

Threshold detectability curves will also be degraded at high image velocities by factors such as the image refresh rate and the basic parameters of the human visual system. It should also be realized that applying movement to the external environment as depicted on a visual simulation system, rather than to the aircraft itself as in the real world, may effect the performance of the human visual system.

Several techniques can be used for the measurement of static MTFA but no known techniques exist for the measurement of dynamic MTFA. A performance metric based on tasks similar to that used by Boynton and Boss seems to be an attractive method for measuring dynamic resolution.

TEMPORAL PROPERTIES

Establishing general procedures for the measurement of temporal properties is difficult due to the variety of techniques used for the generation of visual scenes. The following characteristics were determined to be significant and techniques for their measurement are described in the report of the working group.

- Excursion limits (i.e., maximum velocity)
- Time lags
- Noise
- Linearity
- Hysteresis
- Thresholds

These characteristics are applicable to all types of visual simulation and are particularly important when considering pilot or aircraft performance in closed-loop situations. Ideally, the measurements should be made at the pilot eyepoint.

Measurements made at the input to the display device are usually more convenient although allowances should be made for the properties of the display device or video link itself. Most of the characteristics will be affected in some way or other by the display, i.e., threshold will be affected by the vernier resolution and time lags will be affected by the refresh rate and response time of the displays.

Perhaps the most interesting aspect of the video link, and one about which we have very little knowledge, is the illusion of smooth movement created by television displays.

The phenomenon of apparent motion created by a succession of static images having appropriate spatial and temporal relationships has been known for many years. Apart from its obvious use in the television and motion picture industries, it has provided an interesting analytical tool which has generated a considerable amount of data concerning the conditions which enable smooth continuous motion, jerky motion or succession to be perceived. Many of the anomalies often seen in current visual simulation systems can be attributed to a change in the perception of apparent motion by the human visual system. Stroboscopic effects sometimes seen with runway markings are a good example of this. Interlace crawl (in which one-half of the raster lines seem to disappear while the remaining one-half move slowly up the screen) is caused by the interlaced raster structure being perceived as a set of horizontal lines moving a single line spacing in one field time. The breakdown of smooth motion seen on systems using random texture may be explained by Julesz's ([8]) experiments with random dot arrays. He found that the spatial separation between successive exposures could not exceed 15 arc minutes for motion to be seen. Smooth motion can be seen with discrete objects when the spatial separation is as much as 4°. Braddick ([9]) speculated that the difference was due to two distinct levels of processing in the visual system being responsible for the interpretation of apparent motion.

The motion is random dot arrays seems to be determined by a lower-level process based on directionally selective neurons while the more general form of apparent motion is determined by an upper-level process using interpretive techniques based on the overall situation.

The question arises as to whether or not our perceptual experience of apparent motion is different from that of real motion and whether or not the visual system characteristics associated with real motion can be applied to apparent motion. A corollary to this question would be to determine how the characteristics of apparent motion are affected by the characteristics of the display.

CONCLUSIONS

The main task of FMP Working Group 10 was to define the essential characteristics of visual simulation systems and to recommend suitable measuring techniques. A certain amount of research is still needed before a standard set of procedures can be recommended for all characteristics, however, such research will have limited value unless an attempt is made to answer the three questions raised in the introduction. These questions can perhaps be summarised by one, i.e., what visual cueing is necessary in a simulator to obtain effective training (or research)? One of the recommendations of the joint AGARD working group on fidelity requirements for pilot training was to establish AGARD working groups to pursue the entire training effectiveness question. AGARD cannot perform any research itself but the multinational, multidisciplinary approach used by AGARD seems ideally suited for the task of defining the required research.

Major General Abrahamson opened the 1980 Interservice/Industry Training Conference by giving the entire industry, including the users, a C rating as regards performance. An A rating is probably unattainable as it would imply perfection, however, it should be possible to achieve a B rating during this decade if a concentrated attempt is made to answer the training effectiveness question.

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2 AGARD Advisory Report No. 159, Fidelity of Simulation for Pilot Training (1980)

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4 Matsubayashi, A.; "Forschung uber die Tiefenwahrnehmung", IX Acta Soc. Opthal. Jap 1938, German Abstract, IBID, 133; and Ber. G Es.Physiol., Vol. 112, pp. 290-291.

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6 Snyder, H.L.; Chap. 3 of "Perception of Displayed Information", edited by L. Biberman, Plenum Press, New York, 1973.

7 Boynton, R.M.; Boss, D.E.; "The Effect of Background Luminance and Contrast upon Visual Search Performance", Illuminating Engineering, April 1971, pp. 173-186.

8 Julesz, B.; "Foundation of Cyclopean Perception", Chicago; University of Chicago Press, 1971.

9 Braddick, O.; "A Short Range Process in Apparent Motion", Vision Research, 1974, 14, pp. 519-527.

ABOUT THE AUTHOR

Brian Welch obtained a BSc in Physics from University College, London, in 1960. He joined CAE Electronics in 1965 and has worked on several aspects of flight simulators. Since 1970 he has specialized in Visual Simulation and was responsible for the development of a modelboard visual system. He has been actively engaged in developing and promoting the use of head- and eye-slaved imagery for several years and is currently responsible for the development of a Helmet-Mounted Display for the U.S. Air Force which is being funded jointly by the U.S. and Canadian Governments.